



## Sediment mixing in the tropical Pacific and radiolarian stratigraphy

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[1] The reworking of older radiolarian microfossils into near-surface sediments of the tropical Pacific has long been the source of confusion for the development of radiolarian stratigraphy and of puzzlement over the mechanism(s) that could effect such pervasive reworking. Widespread dissolution “pits” in the sediments of the tropical Pacific are believed to be associated with hydrothermal circulation cells in the older oceanic crust and are here linked to processes which expose older sections and inject older non-carbonate material into near-bottom waters. Discharging waters of these circulation cells tend to dissolve carbonate in near-surface sediments; thus, only the non-carbonate material (including radiolarians) is preserved and reworked into younger sediments. Results from the study of two sites in the tropical Pacific indicate that reworked older, stratigraphically important radiolarians are less than 2% of the total radiolarian assemblage. This constitutes a minimum estimate of the amount of reworked, non-carbonate material in the younger sediments. The oldest reworked radiolarians are no more than 10 m.y. younger than the underlying basement, and radiolarians from the entire older section above that level can be found in the reworked material. A time series of the flux of reworked material at one site is not constant but instead has varied by a factor of 3 to 4 over the past 2.5 m.y. During times when the flux of reworked material is particularly low, the proportion of older, more robust radiolarians is larger.

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## 1. Introduction

[2] Sediment samples from the tropical Pacific containing microfossils of Radiolaria were collected on the *H.M.S. Challenger* Expedition and extensively studied by *Haeckel* [1887]. He illustrated hundreds of radiolarian species and developed a taxonomic system for them that, for the most part, still stands. However, the stratigraphic reasoning of the late 19th and early 20th centuries accepted that the law of superposition strictly applied to the sediments of the deep sea; thus, any microfossil of a planktonic organism found in surface sediments of the deep ocean must have been living recently in the overlying ocean. This led to a widely held conclusion that radiolarians had very long stratigraphic ranges and were not useful for age determination [e.g., *Haeckel*, 1887; *Shrock and Twenhofel*, 1953; *Campbell*, 1954] (see *Sanfilippo et al.* [1985] for a more complete history).

[3] But why would this particular planktonic group have many species whose range extended from the Eocene into the modern times, whereas others did not? It was not until William Riedel started looking at piston cores from the tropical Pacific that this mystery was solved. He was able to show that deeper in the recovered sections there were relatively pure Tertiary radiolarian assemblages that in near-surface sediments were frequently found immixed with species of radiolarians that were known to be living in the plankton [*Riedel*, 1952, 1957]. Somehow these older fossil forms became reworked with younger, even modern sediments.

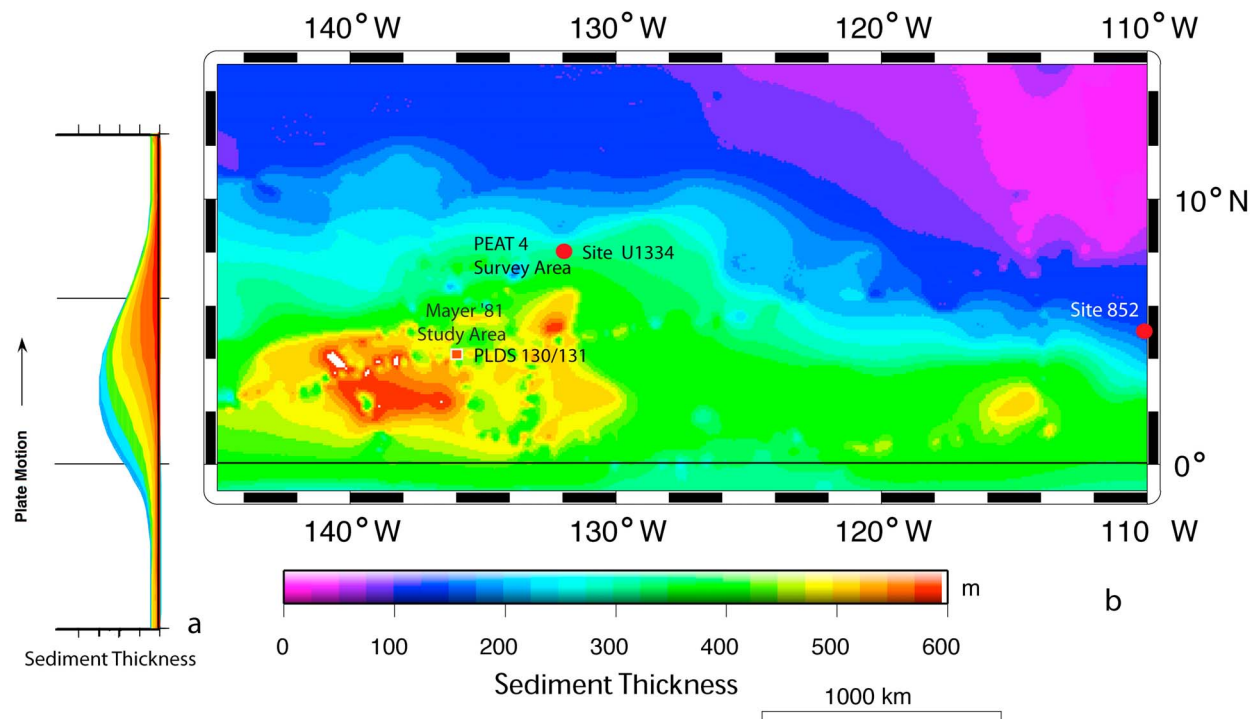
[4] Thus, one mystery was solved and another exposed. By what means could 50-myr old specimens appear in modern sediments? A small part of the answer lay in the evolutionary trend of the radiolarians themselves. The older, Paleogene forms had much more robust tests than those of the younger Neogene and Quaternary. They were able to survive dissolution in the deep waters of the Pacific while the younger, more fragile forms could not [*Moore*, 1969; *Lazarus et al.*, 2009]. A second, more important factor was the impact of plate tectonics on the distribution of sediments in the tropical Pacific. New crust is being formed at the East Pacific Rise in the far eastern Pacific and the Pacific plate has been moving to the northwest through most of the Cenozoic. As a result of this motion the mound of biogenic sediment that collects under the high productivity zone of the Pacific equatorial divergence is slowly being displaced to the north and west. This displacement has moved the thick

accumulation of sediments representing the early Cenozoic equatorial region of high productivity to the northern flank of the present-day, rather narrow zone of high productivity (Figure 1). In this way the older equatorial sediments are not being buried rapidly by a high rain rate of biogenic debris from later times (Figure 1a). As a result of the Pacific plate movement, the pattern of piston and gravity cores recovered in this region during the latter half of the 20th century showed that the farther north of the equator, the older the reworked radiolarians found in the near-surface sediments (Figure 2).

[5] We know that in the tropical Pacific the pelagic rain of sediments settle preferentially in basins rather than on hill tops by a factor of  $\sim 1.3$  [*Tominaga et al.*, 2011]; but this is a syn-depositional process. Aside from the insights provided by plate tectonics, there was very little offered to explain the pervasive occurrence of reworked radiolarians in the near-surface sediments of the tropical Pacific. It was noted that the age of the reworked older species in a sample were never greater than the age of the crust at the sample site [*Moore*, 1995], suggesting that the reworked material was not transported great lateral distances before being redeposited. However, beyond this there was never any plausible mechanism to explain the reworking of radiolarians in the near-surface sediments of the tropical Pacific.

[6] The continued study of radiolarian stratigraphy in the Deep Sea Drilling Project and Ocean Drilling Program drill cores greatly increased our ability to document the age range of the older specimens being mixed into the younger sediments [e.g., *Nigrini et al.*, 2006]; however, allied stratigraphic studies of the same material using the carbonate microfossils rarely showed the presence of any reworked older forms in the carbonate fraction of these sediments. In this regard the mystery seemed to deepen even further.

[7] Recent evidence of hydrothermal activity in the old Pacific crust [*Michaud et al.*, 2005; *Bekins et al.*, 2007; *Moore et al.*, 2007] may provide the answer to this longstanding mystery of radiolarian stratigraphy. In the circulation of ocean waters through the older Pacific crust, the bottom waters entering a circulation cell through the fractured basaltic basement are warmed from geothermal heat causing them to become more saturated with respect to calcium carbonate, as evidenced by calcite veins deposited in the fractured basalt of the upper crust [*Bekins et al.*, 2007]. As the waters rise and eventually escape from the crustal aquifer through exposed basalt or fractures in the overlying



**Figure 1.** Central tropical Pacific sediment thickness and site locations. (a) Diagrammatic cross section of sediment mound as it collects pelagic sediment beneath the equatorial divergence and slowly moves northwestward on the Pacific plate. Oldest sediments in red; youngest in blue. (b) Total thickness of biogenic sediment (in part from D. L. Divins (NGDC Total Sediment Thickness of the World's Oceans and Marginal Seas, <http://www.ngdc.noaa.gov/mgg/sedthick/sedthick.html>) [see also Mitchell, 1998] and location of sites used in this study. Solid black line indicates the equator on which the modern zone of high productivity is centered, extending 1° to 2° north and south.

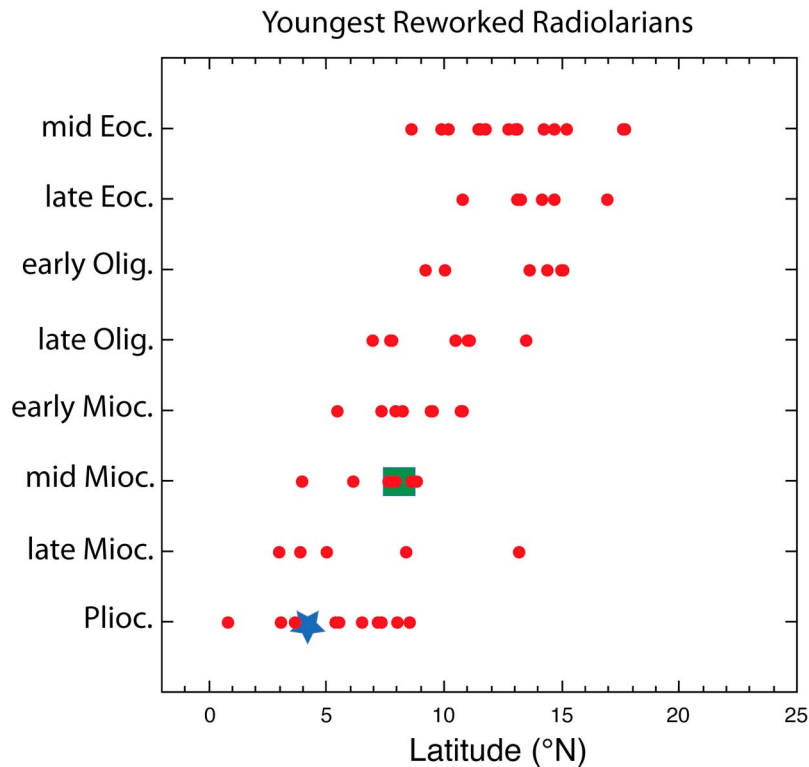
sediments, they cool and become very under saturated with respect to calcium carbonate; and thus, are very corrosive to any carbonate in the upper sediment column through which they pass. These waters are thought to create “pits” in surface sediments through this corrosive action [Bekins *et al.*, 2007; Moore *et al.*, 2007]. Such pits are common throughout the tropical Pacific Ocean [Mayer, 1981; Michaud *et al.*, 2005; Bekins *et al.*, 2007; Moore *et al.*, 2007]. They may be limited to areas where the overlying sediment cover is between 150 m and 600 m thick and appear to occur at an average density of 1 pit per 210 km<sup>2</sup> [Moore *et al.*, 2007]. If evenly spaced, this would mean each pit would lie within a circle with a radius of a little over 8 km.

[8] The impact of these hydrothermal convection cells on biogenic silica is quite different from their impact on biogenic carbonate. As the waters circulating in the upper crust warm, they become more corrosive with respect to silica [Moore, 2008a] and appear to dissolve the siliceous microfossils in the lowermost section of the overlying sediments

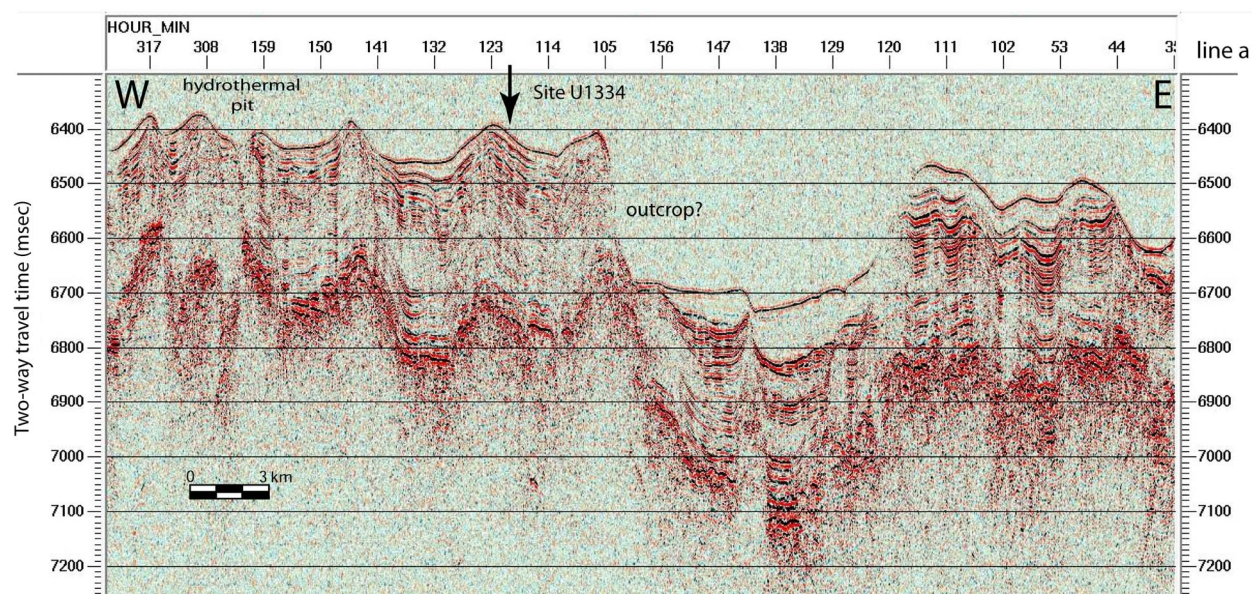
(usually <40 m and rarely >120 m above basement), and then as the waters diffuse upward through the basal sedimentary section and cool, they deposit the silica as chert [Moore, 2008b]. As these cooler waters are vented back into the deep ocean, they appear to be sufficiently corrosive to create pits in carbonate-rich sediments; however, they should be much closer to saturation with respect to silica than the bottom waters themselves. Thus, we would not expect these waters to dissolve siliceous microfossils in the near-surface sediments.

[9] There is evidence that the creation and continued growth of these dissolution pits can erode the sedimentary section and lead to the exposure of older Cenozoic sections at or very near the seafloor (Figure 3) [Moore *et al.*, 2007, Figures 4 and 5]. The corrosive waters that are expelled from these pits may destroy the carbonate microfossils with which they come into contact rather than suspending them in the near-bottom waters of the ocean; but what about siliceous microfossils? Could the venting of these hydrothermal cells be the means by which older radiolarians are injected into the

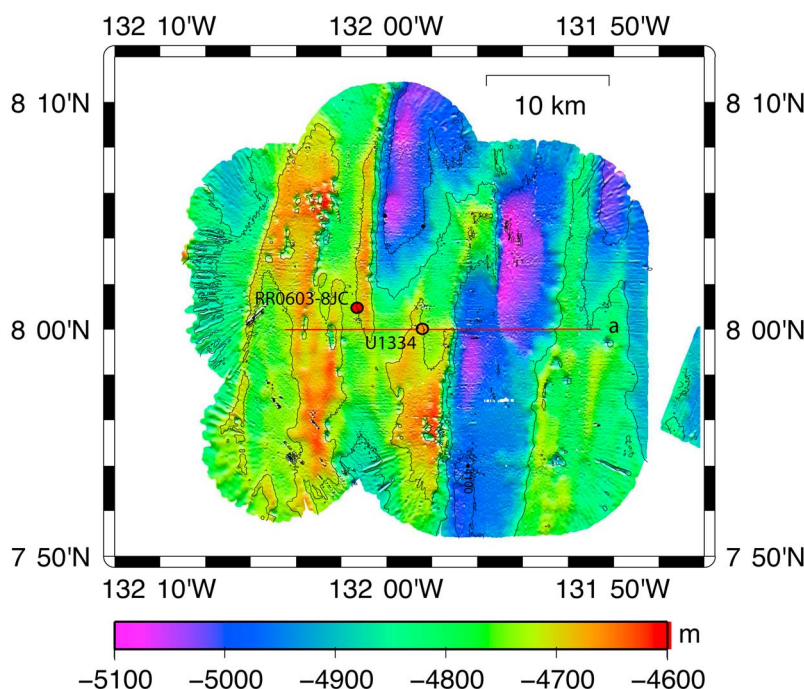




**Figure 2.** Age of youngest reworked radiolarians found in piston cores from the central tropical Pacific (filled circles; data from *Riedel and Funnell* [1964] and T. C. Moore Jr. (unpublished data, 1968)). A star denotes the latitudinal position and youngest reworked fossil age from the *Mayer* [1981] study area. A square denotes the latitudinal position and youngest reworked fossil age from the PEAT 4 area.



**Figure 3.** A west to east seismic cross section from the PEAT 4 survey area through the location of IODP Site U1334 (see Figure 4 for line a location).



**Figure 4.** Swath bathymetry map of PEAT 4 site survey area [Pälike *et al.*, 2010]. Locations of piston core RR0603–8JC and IODP Site U1334 shown as filled circles. Black lines indicate positions of seismic data shown in Figure 3 (line a).

near bottom waters, where they are subsequently reworked into near-surface sediment through bioturbation and tidal currents?

[10] In this paper we look at two separate sites in the central tropical Pacific, one close to the thickest part of the mound of biogenic sediment and one on its northern flank at a latitude where Miocene – Oligocene radiolarians are commonly found immixed in the near-surface sediments (Figures 1 and 2). We evaluate how much of the stratigraphic column at a particular site is actually represented by reworked material in the near-surface sediments, and whether or not this reworking is consistent with older radiolarians being brought to the surface by hydrothermal “springs.” We also delve into an estimate of how much material may be reworked into the uppermost sediments and whether the amount of reworking varies with time.

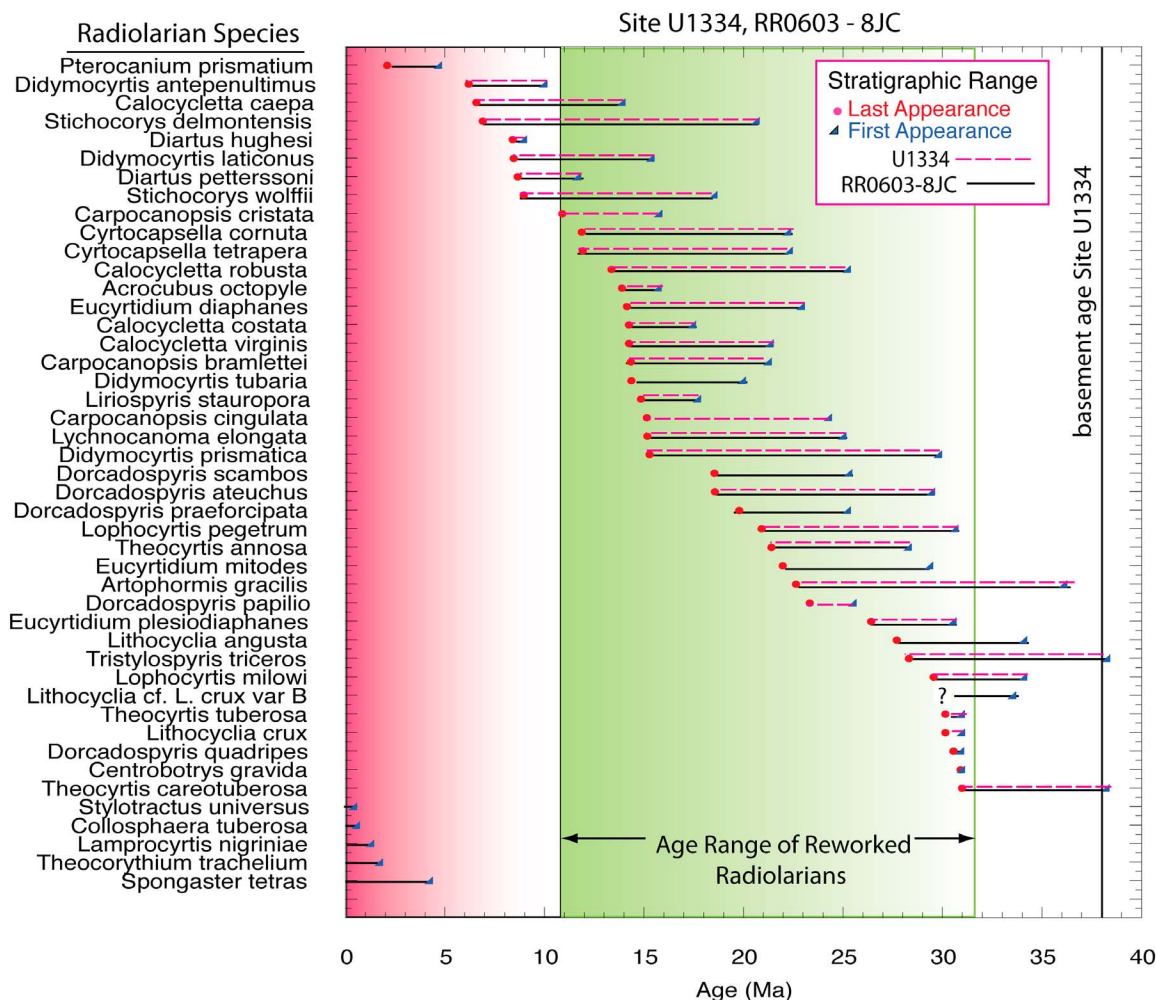
## 2. Materials and Methods

[11] For the north-flank site, we look in detail at the near-surface sediments recovered in a piston core (RR0603–8JC) taken in a well-surveyed area (PEAT 4) of the central tropical North Pacific [Moore *et al.*, 2007; Pälike *et al.*, 2010]. The age range of radiolarians found in the near-surface

sediments of the piston core are compared to the age range of sediments recovered in a nearby drill site, IODP (Integrated Ocean Drilling Program) Site U1334 (Figures 1 and 3–5) in order to determine to what degree the microfossils present in the sedimentary section at this location are represented in the uppermost sediments of the piston core. For the axis of the equatorial Pacific biogenic sediment mound we examine well-dated piston cores (PLDS 130PC and 131PC [Mayer, 1981]) located next to what is thought to be a hydrothermal pit (Figure 1). In these cores we evaluate the time-varying amount of reworked material mixed into the sediment over the last ~2.5 m.y.

### 2.1. Bathymetry

[12] The PEAT 4 area was mapped using data acquired with a 12-kHz hull-mounted Simrad EM120 swath mapping system as described in Moore *et al.* [2007]. The resulting maps have a horizontal resolution of around 100 m near the center of the swath, limited by the filtering required to reduce effects of acoustic noise from other hull-mounted sonars. Toward the outer edges of swaths, resolution is limited by refraction, irregular ship motion, and other problems, illustrated by the



**Figure 5.** Age range [Nigrini *et al.*, 2006] of radiolarian species found in Core RR0603–8JC (solid line) and in the upper part of Site U1334 (dashed line). Ranges of older reworked radiolarian species (i.e., having Last Appearance Datums >9 Ma) found in the upper sedimentary section (younger than ~9 Ma) are encompassed in shaded green area. The age range of these older species spans at least 31 m.y. See text for stratigraphy discussion.

ragged or “noisy” appearance of the outer data (Figure 4).

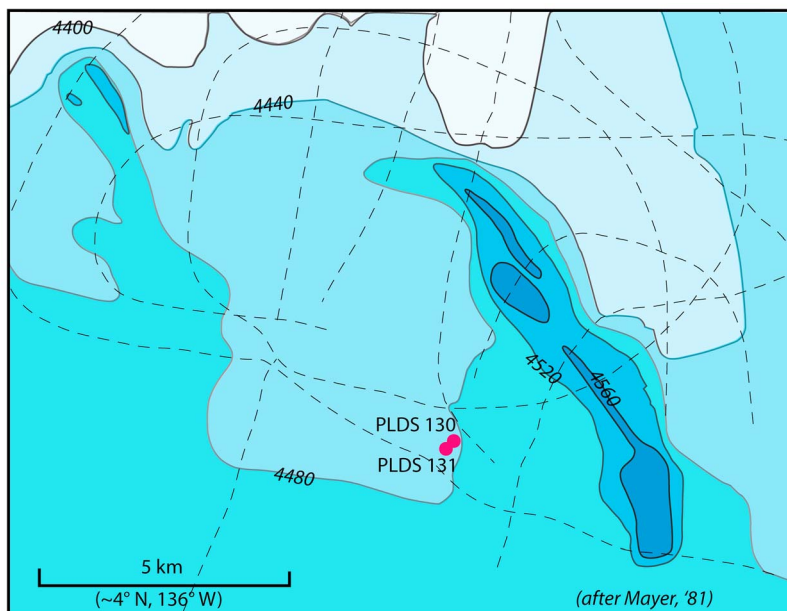
[13] The Mayer [1981] map survey is based on high-resolution 125-kHz data collected with the Deep-Tow instrument package towed close to the seafloor, a state-of-the-art means of obtaining high-resolution profiles of the seafloor topography in 1981. The Deep-Tow survey was navigated relative to a transponder array placed on the seafloor. Side-looking sonar data collected from the Deep Tow provided additional seafloor coverage over the area surrounding the transects (~1/2 km to either side of the instrument).

## 2.2. Biostratigraphy

[14] Sediment samples of ~2 cm<sup>3</sup> were taken at 150 cm intervals at section breaks in core RR0603–8JC

(8 samples total). Samples from Site U1334 were taken at ~3 m intervals [Pälike *et al.*, 2010]. The carbonate records for cores PLDS 130PC and PLDS 131PC and PG (gravity core taken with the piston core) were correlated by Mayer [1979] and through this correlation he developed a composite carbonate stratigraphy (denoted herein as PLDS 130/131). As most piston cores lose some of the uppermost sediments in the coring process, the stratigraphic record from the trigger weight core, PLDS 131PG, was correlated to the piston cores and appended to the upper stratigraphic record. The composite record from these cores was sampled for this study at ~10 cm intervals with a sample slice of 1 cm wide, one quarter core (102 samples total). Bulk density data for the PLDS 130/131 core come from Mayer [1979, supplementary material].





**Figure 6.** Bathymetric map of Mayer [1981] study area as surveyed using the Deep Tow instrument package [Mayer, 1981]. Depth in meters below sea level. Track of the Deep Tow instrument shown as dashed lines. Core locations of PLDS 130PC and 131PC shown as filled circles.

[15] Samples for the study of radiolarians were prepared following the procedures similar to those described in Sanfilippo *et al.* [1985]. Sediment samples were placed in a beaker with ~50 ml of 15% H<sub>2</sub>O<sub>2</sub> to remove organic material and ~50 ml of a 20% HCl solution to remove the calcareous fraction from the sediment. The sample was sieved and washed through a 63- $\mu$ m sieve. If upon visual inspection, the coarse residue was found to contain clumps of cemented clays and radiolarian fragments, the sample was treated for up to one minute in a solution of NaOH with a pH ~ 11, immersed briefly (~15 s) in an ultrasonic bath, and then resieved. This usually disaggregated the cemented clumps and cleaned the radiolarian skeletons so that they could be more easily identified. Residues were randomly settled onto a slide [Moore, 1973] and then a 22  $\times$  40 mm coverslip was mounted on top using Norland Optical Adhesive #61 as a mounting medium.

[16] Slides were studied under a transmitted light microscope at  $\times$ 100 magnification. An estimate of the number of radiolarian specimens on each slide was made by counting the number of specimens in one vertical traverse of the slide (one column, 1.4 mm wide) and in one horizontal traverse (one row, 1.5 mm wide). These values were multiplied by the number of rows and number of columns scanned and averaged to estimate the total number of specimens

examined on the slide. Ages of the radiolarian species are based on the work of Nigrini *et al.* [2006].

### 3. Results

#### 3.1. PEAT 4 Site Survey Area

[17] The site survey core, RR0603–8JC, is located about 5 km to the west of IODP Site U1334 (Figure 4), both are situated on the flanks of topographic highs. Numerous hydrothermal pits are revealed in the survey area (Figure 4) [Moore *et al.*, 2007]. A west to east seismic line through the Site U1334 location (Figure 3 and line a in Figure 4) shows an uppermost acoustically transparent layer of variable thickness, generally thicker in the valleys and thinner on the highs [Tominaga *et al.*, 2011]. This transparent layer is made up of siliceous clay [Pälike *et al.*, 2010]. The scarp to the east of Site U1334 appears to expose nearly the entire stratigraphic section, probably caused by the development of a hydrothermal pit asymmetrically located over the associated basement high [Moore *et al.*, 2007].

[18] Core RR0603–8JC consists entirely of siliceous red clay. Based upon comparison to the Site U1334 sediment profile, RR0603–8JC cored an equivalent to the upper part of the U1334 Lithostratigraphic unit 1, a siliceous clay overlying early

Miocene carbonates [Pälike *et al.*, 2010]. Radiolarians are rare and poorly to moderately preserved in the top two samples (81 cm, 231 cm) [Pälike *et al.*, 2010]. Radiolarians were rare and poorly preserved in samples at 382 cm and 533 cm, and then in deeper samples (684 cm, 835 cm, and 983 cm) they are common and moderately well preserved. The uppermost sample examined in core RR 0603–8JC (81 cm) contains a mixture of upper Pleistocene species and middle Miocene – lower Oligocene species (Figure 5). Below this sample no identifiable radiolarians of Quaternary age were found. Based on scant stratigraphic data, the accumulation rate of this upper section is estimated to be  $\sim 0.18$  cm/kyr. Stratigraphically important radiolarians were counted in the 81 cm sample. Species restricted to the Oligocene – Miocene made up  $\sim 16$  ppt (parts per thousand) of the total specimens present (some of which may have also been of Oligocene–Miocene age). All the reworked species found in the remaining samples range in age from early Oligocene to middle Miocene (Figure 5). No species restricted to the interval between  $\sim 4$  Ma and 7 Ma were found. The sample at 684 cm contained the first down core “in situ” Neogene radiolarian assemblage and has an approximate age of 7 Ma. At this level the radiolarians are dominantly from the upper Miocene with only traces of older Miocene and Oligocene species. The transition between *Diartus petterssoni*/*D. hughesi*, dated at 8.76 Ma [Nigrini *et al.*, 2006], occurs between 835 cm and 985 cm.

[19] The uppermost cores from Site U1334 contain no Quaternary radiolarians in a poorly preserved assemblage of mixed upper Miocene – lower Oligocene species, nearly identical to the reworked assemblage found in core RR0603–8JC (Figure 5). The transition between *Diartus petterssoni*/*D. hughesi* occurs between 5.56 mbsf and 8.15 mbsf (meters below seafloor). A trace of reworked older (early Oligocene) radiolarians are found at least as far down as core U1334A - 3H at a depth of  $\sim 27$  mbsf (early middle Miocene sediments [Pälike *et al.*, 2010]).

[20] Sediments recovered from just over basaltic basement at Site U1334 were dated at  $\sim 38$  Ma based on the calcareous nannofossil assemblage [Pälike *et al.*, 2010]. Radiolarians were not preserved in the 10 m interval above basement (the “silica free zone” of Moore [2008b]). The oldest preserved radiolarian found in Site U1334 (*Calocyclas bandyca*) has an age range of 36.7 Ma to 34.6 Ma [Nigrini *et al.*, 2006; Pälike *et al.*, 2010]. The oldest radiolarians found in the reworked

assemblage is no older than  $\sim 31$  Ma; thus, material from all but  $\sim 35$  m ( $\sim 4$  m.y.) of the entire stratigraphic column containing radiolarians at Site U1334 ( $\sim 326$  m) [Westerhold *et al.*, 2012] is represented in the reworked radiolarian assemblage.

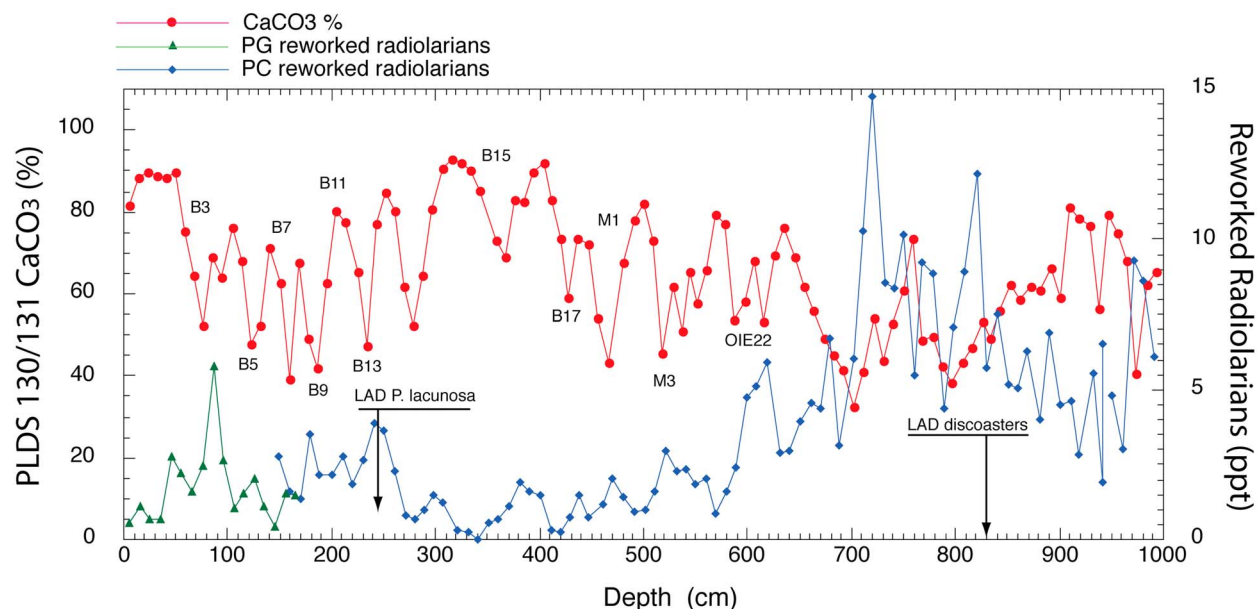
### 3.2. The Mayer [1981] Study Area

[21] Dashed lines on the map of the Mayer [1981] survey area (Figure 6) indicate the track of the Deep-Tow instrument. Their irregular spacing limits the horizontal resolution that the map can offer; however, the vertical resolution of the profiles exceeds the resolution of swath mapping techniques used in the PEAT 4 area and gives a detailed picture of the morphology of the pit (or trough, as described by Mayer [1981]). These profiles show outcropping sediment layers with ledges on the sloping sides of the pit. The pit slopes in some places attain angles  $>60^\circ$  [Mayer, 1981]. The maximum depth of the depressions is close to 100 m, and a core taken on the side of this depression recovered sediments of early Miocene age [Mayer, 1981].

[22] There are no drilling sites close to this survey area; however, based on seismic reflection records, sediment thickness in the area varies between 400 and 500 m [Mayer, 1981]. Based on the basement age of nearby drill sites and on magnetic anomaly patterns, the age of basement in the survey area is estimated to be  $\sim 41$  Ma [Mayer, 1981].

[23] Piston cores collected in the survey area were navigated relative to the seafloor transponders, resulting in very precise (relative) positioning. Two of the cores (PLDS 130PC and 131PC) were close together and within 2 km of the pit (Figure 6). Based on the correlation of the composite carbonate records of these cores to the carbonate stratigraphy of Hays *et al.* [1969], oxygen isotope stratigraphy, and a few biostratigraphic datums (Figure 7), Mayer [1979] was able to establish a time scale for PLDS 130/131. In this paper we have used this time scale as a starting point and have correlated this core to the density record (as a proxy for carbonate) of ODP Site 852 drilled in the eastern tropical Pacific (Figure 1). The Site 852 record has been tuned to the orbital time scale by Shackleton *et al.* [1995] to give a detailed chronostratigraphy (Figure 8). The program AnalySeries 2.0 [Paillard *et al.*, 1996] was used in establishing this correlation. The carbonate record of the PLDS 130/131 composite matches well the density record of Site 852 back to about 1.2 Ma. Below that point the carbonate record shows much less detail and the



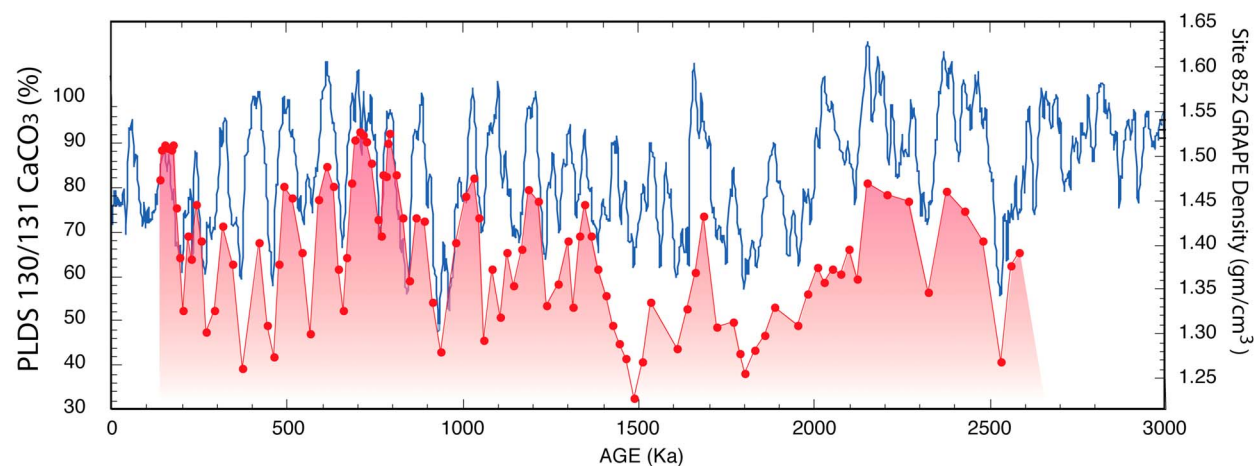


**Figure 7.** Carbonate concentrations (filled circles) and concentrations of reworked older radiolarians (filled diamonds) in the combined PLDS 130/131 section (see text). Carbonate stratigraphy (indicated by letters and numbers) from *Hays et al.* [1969] as assigned in *Mayer* [1979]. Biostratigraphic last appearance datums (LADs) as defined in *Mayer* [1979]. PC refers to the combined sections of piston cores PLDS 130/131 and PG to the gravity core taken with PLDS 131PC [Mayer, 1979].

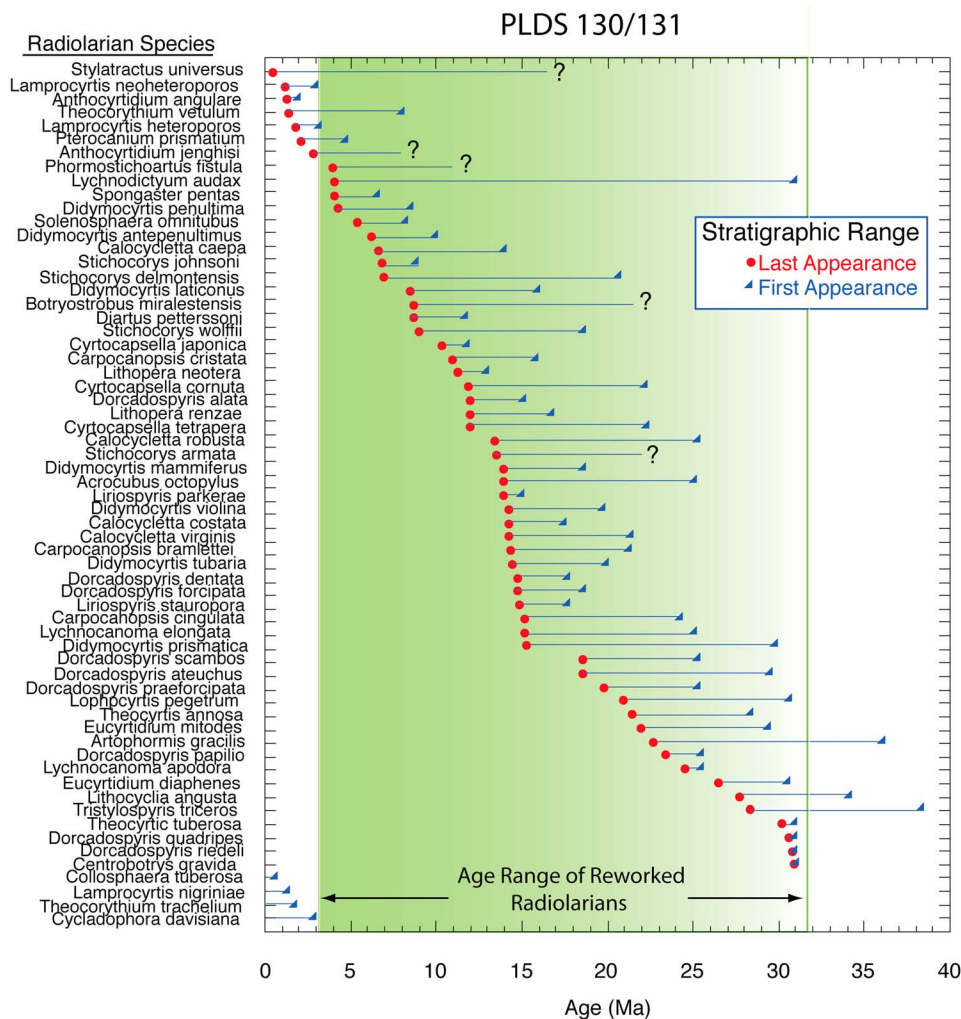
match is less robust. The sedimentation rates range from  $\sim 0.5$  cm/kyr, decreasing down core to less than 0.3 cm/kyr. From acoustic records taken with the Deep-Tow instrument, an angular unconformity was detected in the area immediately surrounding the pit, just below the penetration depth of the two cores studied here [Mayer, 1981]. The unconformity was penetrated in one of the other PLDS cores and it

was estimated to be missing the record between  $\sim 4$  Ma and 7.8 Ma [Mayer, 1981] - very similar to the age of the missing record in RR0603-8JC.

[24] Stratigraphically important species were counted in the PLDS 130/131 composite record. Beginning with the topmost sample a few specimens of older Cenozoic species were found immixed with



**Figure 8.** PLDS 130/131 combined carbonate record (filled circle data points) adjusted to the orbitally tuned time-scale of the ODP Site 852 density record (used as a proxy for carbonate concentrations) [Shackleton et al., 1995]. Adjustments made using the AnalySeries Program of Paillard et al. [1996].



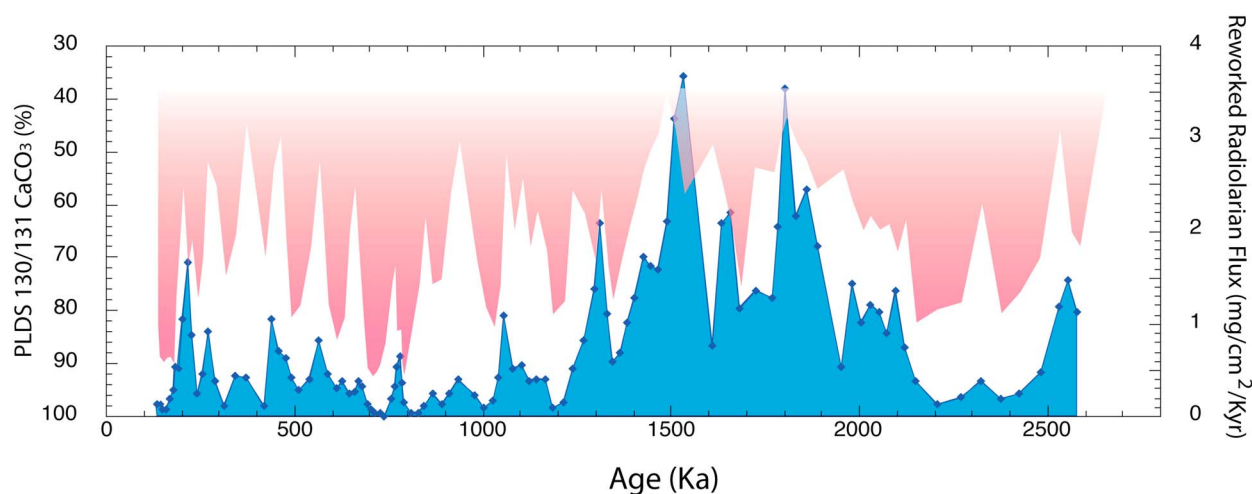
**Figure 9.** Age range [Nigrini *et al.*, 2006] of radiolarian species found in the PLDS 130/131 combined section. Ranges of older reworked radiolarian species (i.e., having Last Appearance Datums >3 Ma) found in the upper sedimentary section (younger than ~3 Ma) are encompassed in the shaded green area. The total age range of these older species spans at least 34 m.y. See text for stratigraphy discussion.

Quaternary radiolarians (Figures 7 and 10 and Table S1 in the auxiliary material).<sup>1</sup> The number of individual reworked older species (Figure 9) found in the PLDS 130/131 core is greater than that found in Core RR0603–8JC, but this is likely a result of examining more than ten times the number of samples in the study of PLDS 130/131 and examining, on average, more specimens per sample. Some of the species whose ranges span the age range of the hiatus (noted above) are found in the samples (e.g., *Spongaster pentas* and *Solenosphaera omnitubus*). A few of the species that range into the upper Pliocene (e.g., *Pterocanium prismatium* and *Anthocyrtidium jenghisi*) are found near the base of PLDS 130/

131, albeit above the level of their established last appearance datum (LAD) [Nigrini *et al.*, 2006]. The stratigraphy of the Quaternary radiolarians [Nigrini *et al.*, 2006] in PLDS 130/131 agrees well with the orbitally tuned time scale down to about 660 cm (~1.4 Ma). Below that depth the accumulation rate drops and reworking of the sediments disturbs the stratigraphic order of the radiolarians.

[25] The total number of specimens of reworked older species were summed and expressed as parts per thousand of the total number of radiolarians counted on each slide (Figure 7). This record shows that the reworked material is much more abundant in the lower part of the core where carbonate content and sedimentation rates are lower.

<sup>1</sup>Auxiliary materials are available in the HTML. doi:10.1029/2012GC004198.



**Figure 10.** Carbonate concentrations and flux of reworked radiolarians versus age in the combined PLDS 130/131 section. Reworked radiolarian data shown as filled diamond data points and solid filled in curve. Carbonate concentrations shown as a shaded curve (inverted scale).

[26] In order to estimate the supply rate of reworked older radiolarians to the PLDS 130/131 sediments, we assume that most of the non-carbonate fraction is composed of biogenic silica [Farrell *et al.*, 1995; Hovan, 1995]. Very little dust was found in the middle-early Miocene section of DSDP Site 574, drilled at nearly the same latitude but 2 1/2 degrees east of the Mayer [1981] site [Piela *et al.*, 2012]. At Site 574 the median dust values estimated from  $^{232}\text{Th}$  content was 0.7%.

[27] We then use the saturated bulk density of the samples studied by Mayer [1979] and the time scale generated in this study to calculate a mass accumulation rate (MAR) for the sediments in PLDS 130/131. By multiplying the fraction of non-carbonate material by the MAR we estimate the flux of “opal” to the sediments and multiply this flux by the fraction of reworked older radiolarians to estimate the flux of reworked material to the sediments through time. It should be emphasized this flux of reworked material is only an index of the amount of actual reworked non-carbonate material that was contributed to the sediment. The sum of the species composing this index probably never exceeds 20% of the assemblage in which they are normally found, and the non-carbonate fine fraction ( $<63\ \mu\text{m}$ ), in the PLDS 130/131 section generally is about 20 times larger than the non-carbonate coarse fraction. Thus the actual amount of reworked non-carbonate material being supplied to these sediments could be as much as two orders of magnitude more than indicated by the index shown in Figure 10.

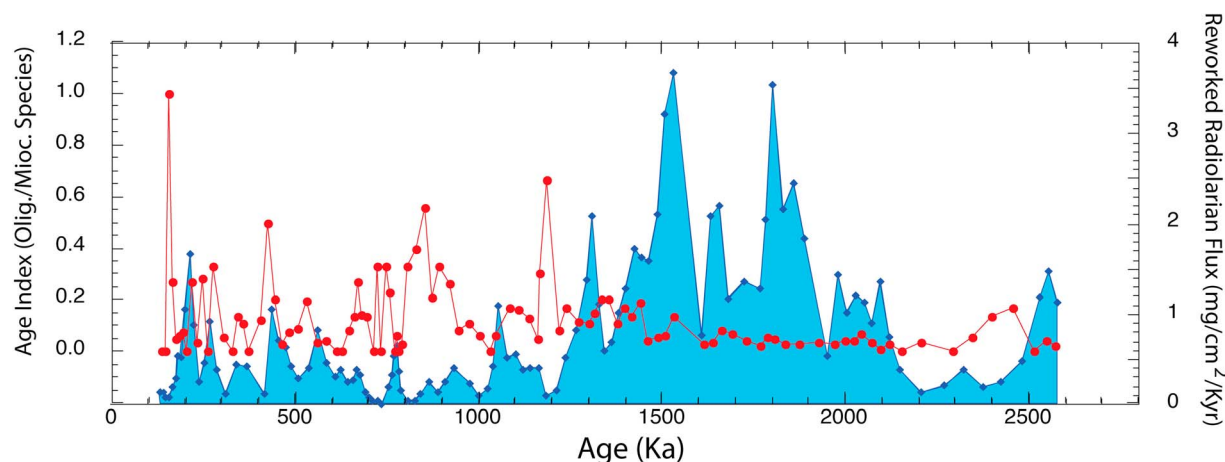
[28] The flux of reworked material indicated by this index is not large (Figure 10). It varies between less

than a fraction of  $1\ \text{mg}/\text{cm}^2/\text{kyr}$  to a maximum of  $\sim 3.5\ \text{mg}/\text{cm}^2/\text{kyr}$ . Back to 1.2 Ma it averages  $\sim 0.5\ \text{mg}/\text{cm}^2/\text{kyr}$  and is highly variable. Below that level, between 1.2 Ma and 2.1 Ma, there is a marked increase in the flux of reworked material, and then deeper in the section the amount returns to  $<1\ \text{mg}/\text{cm}^2/\text{kyr}$ .

[29] The pattern of variation in the reworked material matches to some degree the pattern of carbonate concentration (Figure 10), with low carbonate intervals often having more reworked material. This relationship is far from perfect and may, to some degree, reflect imperfection in the detailed estimates of sediment accumulation rates that were used. However, the preservation of carbonate and particularly biogenic silica (Table S1 in the auxiliary material) in this interval argues against a very low accumulation rate during the maximum flux of reworked radiolarians.

[30] The data in Figure 10 gives an indication that the amount of reworked material deposited at the core site varied with time, but did the age distribution of reworked microfossils change over the last 2.5 m.y. as well? To evaluate this possibility we ratio the number of Oligocene age specimens to the number of Miocene age specimens in each of the samples. We have used the more common, easily recognizable species for each age in this index. For the Oligocene we have summed *Theocyrtis tuberosa*, *T. annosa*, and *Artophormis gracilis*; for the Miocene we have used *Stichocorys delmontensis*, *Cyrtocapsella cornuta*, *C. tetrapera*, and *Didymocyrtis laticonus*. Based on the general abundance of these species within their stratigraphic range we





**Figure 11.** Flux of reworked radiolarians (filled diamond data points and solid filled in curve) and ratio of Oligocene species group to Miocene species group (see text) versus age in the combined PLDS 130/131 section (filled circles).

would expect this ratio to vary somewhere between 1.0 and 0.6 if the two ages were equally represented. As shown in Figure 11, the ratio is usually  $<0.3$ , indicating that the older species tend to be less abundant. In the lower part of the core, where sediment accumulation rates are lower and the overall abundance of reworked radiolarians in each sample is greater (Figures 7 and 11), the ratio is fairly constant at  $\sim 0.3$ . In the upper part of the core the ratio is much more variable with peak ratios reaching from 0.5 to almost 1.0. These maxima tend to occur where the amount of reworked material is very small (Figure 11). This may just reflect the variability inherent in a ratio based on such small numbers; however, the fact that nearly every minimum in reworked material is associated with a peak in the age ratio, suggests that there may be other causes. The Oligocene radiolarian assemblage, in general, has more robust shells than the Miocene assemblage [Moore, 1969]; thus preferential preservation of the older species may give rise to these peaks in the ratio when the amount of reworked material is very low.

#### 4. Discussion and Conclusions

[31] Reworked radiolarians in piston cores of the central tropical Pacific plagued the development of radiolarian stratigraphy for nearly a century. The advent of scientific ocean drilling gave us access to deeper sections, largely free of reworked, older specimens or at least diluted by higher sediment accumulation rates to the point that the immixed assemblage was very sparse. These new sections enabled the development of a robust stratigraphy for

this most diverse group of all marine microfossils [e.g., Nigrini *et al.*, 2006]. The development of techniques that allow us to look closely at the topography of the seafloor and the underlying sediments has allowed us to evaluate the processes by which this reworked material is made available to depositional processes operating on and near the seafloor.

[32] Evidence from detailed mapping of the seafloor indicate that the operation of hydrothermal circulation cells in old oceanic crust has led to the development of exhalation pits and the exposure of older sedimentary sections in the tropical Pacific [Michaud *et al.*, 2005; Bekins *et al.*, 2007; Moore *et al.*, 2007]. The chemical changes in the waters transported in these cells leads to the dissolution of carbonate at their exit site, thus creating a pit. Under the right conditions, the erosion associated with pit formation can lead to wholesale exposure of the stratigraphic section (Figure 3). But are such exposures the dominant source of the reworked radiolarians? It does not seem likely, at least in the thicker parts of the sediment mound. These outcropping areas are rather rare on the upper flanks and especially near the center of the biogenic sediment mound in the tropical Pacific, whereas the dissolution pits appear to be relatively common [Moore *et al.*, 2007]. In the dissolution process, the pits themselves expose part of the stratigraphic section – on the order of 100 m in the Mayer [1981] study area. This is barely one quarter of the total sediment thickness at that site. A core from the flank of this pit recovered sediments no older than 18 Ma (*Stichocorys wolffii* Zone [Mayer, 1981; Nigrini *et al.*, 2006]), whereas the basement age is

near 41 Ma at this site and the immixed radiolarians date back to ~31 Ma (Figure 9). Furthermore, Mayer [1981] could find no plausible physical means of both eroding the pit and carrying away the eroded material. Some explanation other than physical erosion and redeposition was needed, but it was only later that his initial work led to the highly plausible explanation of chemical erosion [Bekins *et al.*, 2007]. In their paper Bekins *et al.* [2007] indicate that the dissolution potential of hydrothermal waters heated to temperatures warmer than ~7°C (a low value compared to most downhole temperature measurements in sections thicker than ~200 m) would have the capacity to dissolve the rain of new carbonate falling into the dissolution pit. Furthermore, the average flux of hydrothermal waters from the PLDS area pits required to outpace sedimentation of carbonate through dissolution (~3 m/yr) is well below the maximum in estimates of lateral hydrothermal flow in the basement crust (10 m/yr) [Bekins *et al.*, 2007].

[33] It seems obvious from looking at Figure 3 and from the work of Tominaga *et al.* [2011] that syn-depositional processes can redistribute sediments falling to the seafloor. These processes probably rely on biologic disturbance on the seafloor, bioturbation, tidal currents and topographically induced turbulence to effect a lateral movement of suspended particles. But the pervasive redistribution of particles that originate near the base of a thick sedimentary section requires something more than bioturbation to expose them so they can be moved laterally. We propose that this mechanism is the creation of outcrops of older sediments by the chemical erosion of carbonate in hydrothermal pits (especially pits asymmetrical with respect to crustal highs) and the expulsion of non-carbonate particles, including radiolarian microfossils, from hydrothermal “springs” that form these pits at the seafloor.

[34] The two sites show evidence of two different mechanisms to expose and redistribute microfossils from the lower sediment section. Around Site U1334 (Figures 3 and 4), there is low modern sedimentation because of low surface water productivity, so the 250–300 m of sedimentary section is largely relict from the time Site U1334 was closer to the equator. In this case, fluid flow through the pits probably erodes and enhances the exposure of sediments along the edges of abyssal hills. The hydrothermal pits are concentrated there, and by enhancing erosion, may both bring microfossils up from the lower sediments, and also expose them as the pits coalesce. Given the substantial exposure of sedimentary section seen in Figure 3, it is not possible to rule out the possibility

that all the reworked older radiolarians in the cores studied in this area come from such an outcrop. To verify this would likely require a mapping of the amount of reworked material relative to the positions of outcrops and pits. The data presently available only show us that the range of ages of reworked material is essentially the same at both cored locations (Figure 5), whereas the individual sites are spatially separated by about 4 km, upslope from the outcrop area, and downslope from some of the pits (Figures 3 and 4).

[35] There are no known outcrops near the Mayer [1981] site, where sediments are still depositing at a low to moderate rate (~0.45 cm/kyr) except within the pits. The seismic sections shown by Tominaga *et al.* [2011] from areas of the equatorial sediment mound with sediment thickness and water depth similar to the PLDS area do not show substantial outcrops; however, many pits were identified on swath bathymetry data taken along these same profiles [Moore *et al.*, 2007]. The pits themselves in the PLDS area do not appear to expose sediments older than 18 Ma, even though microfossils as old as 31 Ma are found. In this case, we believe that as hydrothermal waters climb and dissolve their way to the sediment surface through fractures in the sedimentary section [Mayer, 1981; Bekins *et al.*, 2007; Moore *et al.*, 2007], they could carry with them the well preserved siliceous microfossils from the lower part of the section. In such a case, it might be expected that the deeper, older microfossils would be less abundant than those from farther up the stratigraphic section, which appears to be true.

[36] Cores from the two surveyed areas studied here both show reworked older radiolarians in near-surface Quaternary sediments. In both cases the age of the oldest reworked material is less than 10 m.y. younger than the age of basement. This makes a case for exposure of, or transport through, nearly the entire sedimentary section. In the Mayer [1981] area, where no extensive outcrop of the lower section was found, transport through the section seems the more likely alternative. If this is so, why stop at material 10 m.y. younger than the basement; why not material from the very oldest part of the section? Part of the explanation may be the “silica free zone” of Moore [2008b], the basal interval of the sedimentary section from which silica has been dissolved by hydrothermal waters. It is very rare to find siliceous microfossils on or close to basaltic basement [Moore, 2008b; Pålke *et al.*, 2010].

[37] There may also be a link with the positioning of the hydrothermal vents with respect to basement

topography. As discovered by Mayer [1981] and reinforced by Bekins *et al.* [2007] and Moore *et al.* [2007], these vents are usually located over basement highs. The earliest sediments to be deposited in the area would tend to fill in the surrounding valleys and lap onto these highs; thus drill sites such as U1334, which are usually drilled in valleys or on the flanks of basement highs, are likely to encounter sediments over basement that are somewhat older than those found atop the highs themselves. Because the exiting waters in the hydrothermal cells flow through the upper crust of these highs and enter the sedimentary section through fractures in the overlying sediments that are engendered by tensional stress over these highs [Mayer, 1981], the age of transported siliceous microfossils are likely to be measurably younger than the oldest sediments in the adjacent valleys.

[38] Assuming that our proposed mechanism for delivering older material from near the base of the sedimentary section to the seafloor is correct, there is no obvious reason to suspect that the rate of this flux is in any way related to the flux of pelagic sediment to the seafloor from the overlying ocean. The Quaternary siliceous red clay sediments in piston core RR0603–8JC are estimated to have accumulated at a rate near 2 mm/kyr and contain 16 ppt reworked older radiolarians. The peak concentration of reworked radiolarians in PLDS 130/131 is under 15 ppt and occurs in a part of the core in which accumulation rates were 4 mm/kyr and carbonate concentrations were low (just over 30%). The maximum concentration of reworked material is found in intervals where pelagic sediment accumulation rates are comparatively low. But this may not mean that there is a steady supply of reworked material and its concentration depends only on the rate of the pelagic sediment accumulation that dilutes it. Nor does it mean that the supply of reworked older material is distributed in a spatially uniform manner. Estimates of the changing flux of reworked material in core PLDS 130/131 (Figure 10) suggest that this flux can change by a factor of 3 to 4 at this location (assuming the pelagic rain of radiolarians is relatively constant). If this degree of variability relies solely on a changing supply of reworked material, then it suggests that these deep-sea hydrothermal springs, like more familiar hydrothermal springs on land, do not flow steadily, but rather have intervals on increased and decreased activity depending on factors such as heat content of the waters and changes in the ease of passage through a complex fracture system. Large changes in hydrothermal discharge may be recorded in the amount of reworked material

supplied to the surrounding area; however, short-term pulses in discharge are probably smoothed out by the syn-depositional processes that laterally distribute the reworked material.

[39] The index we have devised for the age makeup of the reworked material appears to indicate that the relative abundance of older material did not change greatly at this site over the last 2.5 Ma. The larger variability in this index over the last 1 m.y. seems to be related to the absolute abundance of reworked material and may result from differential preservation of the older material. Sediment reworking and smoothing of the record (as suggested by the Quaternary radiolarian stratigraphy) may have also contributed to the less variable age ratio of reworked material in the lower part of PLDS 130/131 (accumulating at  $\sim 0.17$  cm/kyr) compared to the upper part of the core (accumulating at  $\sim 0.5$  cm/kyr).

[40] We have presented in this study a model that seems to explain the pervasive reworking of older radiolarians in near surface sediment of the tropical Pacific. If this model is correct it relies on a mechanism that must also be of profound importance to the chemistry of the ocean crust, of the sediment column and of the ocean waters themselves. The types of places where hydrothermal discharge is supposed to occur have been identified; however, we have yet to sample such discharge. In fact, we know nothing factual of its chemistry, its discharge rate, the variability of its flow, and whether or not it actually carries particulate material from the bottom of the sediment section all the way to the seafloor. Hydrothermal springs near seafloor spreading centers are receiving much attention. The hydrothermal circulation in the older crust awaits further study.

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